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# Determination of flow orientation of an optically active turbulent field by means of a single beam

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The cross-flow orientation of an optically active turbulent field was determined by Fourier transforming the wander of a laser beam propagating in the ocean. A simple physical model for the measured effect is offered, and numerical simulations are performed. The simulations are in good agreement with measurements, validating the assumptions made in the model. © 2013 Optical Society of America

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The wind direction of the atmosphere is routinely monitored by remote sensing techniques such as LIDAR and SODAR. The measurement principles usually employed are the Doppler shift in applications in which the flow is in the direction of the detecting beam [1] and cross correlation of the scintillation pattern in a crosswind geometry [2]. Here we describe a technique that relies on the beam wander of a single laser beam, measured in two orthogonal directions, to infer the cross-flow direction of an optically active turbulent volume in the ocean. The principles of this technique should apply equally to measurements in the atmosphere.

In order to illustrate the technique, a simple model is used that assumes that the refractive index variations in an optically active turbulent field can be considered to come in the form of spherical cells [3]. Furthermore, these cells are considered to be static in shape on the relevant time scales (Taylor's frozen turbulence hypothesis [4]). If a single such turbulent cell transitions a laser beam whose diameter is small in comparison to the cell, the beam will be deflected as a whole (beam wander) and will not undergo significant distortion [5,6]. In the following, we consider the beam deflection caused by a single cell with an index of refraction smaller than its surroundings (see Fig. 1), moving in a plane perpendicular to the beam. The deflection along the axis parallel to the flow direction will initially be in the direction of the flow as the cell enters the beam, and then against the flow direction as it exits the beam. When the cell is exactly midway, there will be no deflection parallel to the flow. The deflection caused by the same cell in the direction perpendicular to the flow will be to the right if the cell is displaced slightly to the left of the beam, or to the left if the cell is displaced to the right of the beam; no deflection perpendicular to the flow will be observed if the cell is centered on the beam. Here, if the flow is in the positive  $y$  direction and the beam propagates along the positive  $z$  direction, right and left refer to the directions along the positive and negative  $x$  axis directions, respectively, assuming a right-handed coordinate system. Qualitatively, the beam deflection perpendicular to the flow has the

form of a Gaussian-shaped hump toward the left or the right, depending on the position of the cell relative to the beam. The deflection along the flow direction, however, will trace the first derivative of a single Gaussian, i.e., a hump in the direction opposite to the flow followed immediately by a hump in the flow direction. For a cell of higher refractive index compared to its surroundings, the deflections will occur in the opposite directions. In reality, many such turbulent cells will transition the beam in rapid succession and the deflection in time parallel to the flow becomes essentially indistinguishable, at least on a qualitative basis, from the deflection perpendicular

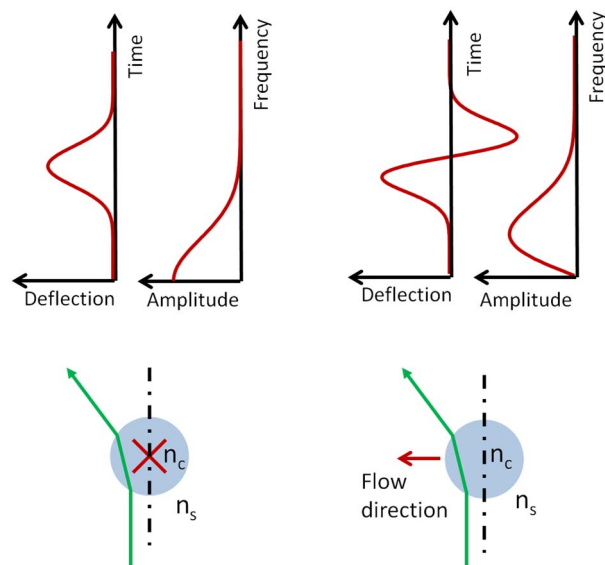


Fig. 1. Left side: beam deflection perpendicular to the flow caused by a single turbulent cell with index of refraction  $n_c < n_s$  if the cell is offset slightly to the right of the beam (flow direction into page). On the right, the beam deflection parallel to the flow direction is shown for a cell entering the beam from the right and flowing to the left. Graphs on top show the beam deflection in time as well as the amplitude of the Fourier transform for the situation depicted on the right and on the left, respectively.

to the flow (see top row of Fig. 3). However, the magnitude of the Fourier transform, in accordance with the shift theorem [Eq. (1)] [7], is invariant of translation in the time domain, and therefore is independent of the time a cell passes through the beam:

$$|F(g(t-a))| = |F(g(t))e^{-i\omega a}| = |F(g(t))|. \quad (1)$$

For example, Fourier transforming the Gaussian-like signal for deflection perpendicular to the flow caused by a single turbulent cell will result in a Gaussian-like magnitude centered at zero frequency regardless of the time the cell transitions. Furthermore, the Fourier transform of the derivative of any function is proportional to the Fourier transform of the function, multiplied by the frequency [Eq. (2)]. In the case of the derivative of a Gaussian, a Gaussian centered at the origin results, but multiplied by its frequency variable:

$$F(g') = \int_{-\infty}^{\infty} g'(t)e^{-i\omega t} dt = i\omega \int_{-\infty}^{\infty} g(t)e^{-i\omega t} dt = i\omega F(g). \quad (2)$$

Since the Fourier transform is a linear operator, the signals from a series of deflections will sum to either a Gaussian or a Gaussian multiplied by the frequency, independent of the time of the deflection. However, the randomly arriving pulses in the time domain will accumulate with random phases in the frequency domain. Therefore the signals from individual pulses interfere, which produces the fast varying, noise-like signal seen in the Fourier transform of both simulated and measured data. The above hypothesis has been tested and qualitatively verified both through experiments and through numerical simulation.

During the recently conducted Bahamas Optical Turbulence Experiment (BOTEX) cruise [8], a multitude of laser beams was projected onto a ground glass plate after propagating a distance of 8.85 m through moving ocean water. The motion of these projections on a ground glass plate was recorded using a high-speed camera (see Fig. 2), and the deflection signals were extracted via a particle-tracking algorithm. The particle-tracking algorithm tracks the center of the individual beams and is therefore relatively insensitive to beam distortion such as focusing and defocusing. A detailed description of the measurement setup and data analysis can be found elsewhere [8,9]. Measurements of beam wander from a single beam in the orientations parallel and perpendicular to the flow (both perpendicular to the laser beam propagation direction) are shown in Fig. 3. Also shown in Fig. 3 are the averaged Fourier transform magnitudes of deflections simultaneously recorded for 13 beams. Similar data-sets were recorded at 12 different depths between 5 and 85 m with weak optical turbulence in the upper layers (where the water temperature is independent of depth) and strong optical turbulence in the thermocline where a pronounced temperature gradient exists (starting below 55 m). At all depths, the difference in the Fourier transformed beam deflection data exhibits the same distinctly different behavior for orthogonal deflections. The bottom

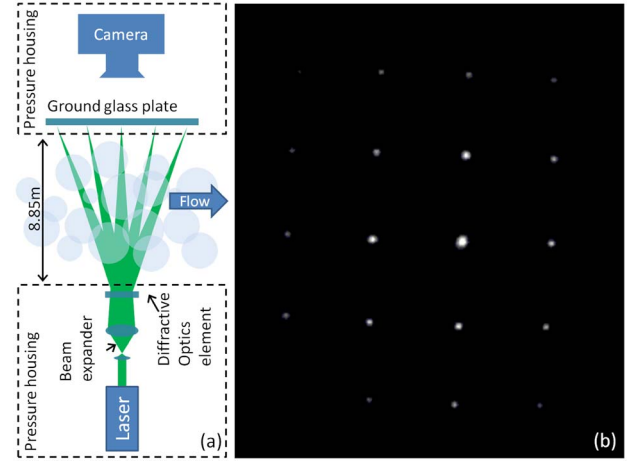


Fig. 2. (a) Experimental setup. (b) Individual laser beams as recorded by the camera from the back of the ground glass plate.

left panel of Fig. 3 shows the averaged Fourier transform of the data along different directions from  $0^\circ$  to  $360^\circ$  in a two-dimensional color plot. On the other hand, as evident from the histograms presented in Fig. 4, no consistent difference could be detected in the variance of the beam deflection along these two directions; i.e., the long-term beam spread function was rotationally symmetric. Hence, as in the time domain (top row of Fig. 3), no conclusions can be inferred about the flow direction in the spatial domain.

In order to numerically simulate the beam deflection along directions parallel and perpendicular to the flow, a randomly spaced series of Gaussian pulses and a randomly spaced series of Gaussian pulse derivatives were generated. In each series, the width of 1000 pulses was

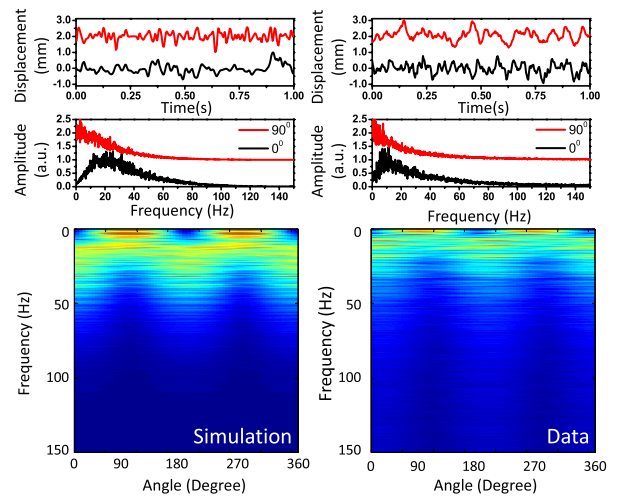


Fig. 3. Simulated beam deflection data on the left and field measurements on the right. Red lines (upper trace) on the top represent beam deflection perpendicular to the flow direction and black lines (lower trace) are beam deflection parallel to the flow direction of a single beam. Middle figures show the averaged fast Fourier transform (FFT) amplitudes of 13 beams parallel and perpendicular to the flow direction in black (lower trace) and red (upper trace), respectively. Bottom graphs show the amplitude of the FFT calculated for angles from  $0^\circ$  to  $360^\circ$  with respect to the flow direction.

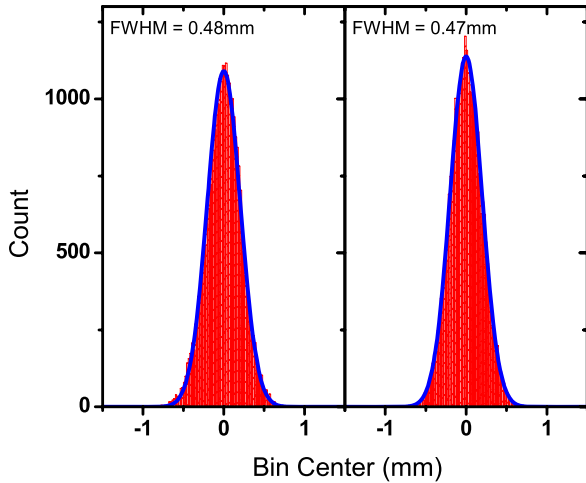


Fig. 4. Histograms of beam centroid position as recorded during BOTEX. The red bars show data at  $0^\circ$  and  $90^\circ$  with respect to the flow orientation. Also shown is a Gaussian fit to the distributions (blue lines) and the variance in terms of full width at half-maximum (FWHM). The small difference in the variance is not correlated to the flow orientation as can be found by comparing the numbers at different measurement depth (data not shown).

randomly altered consistent with the transition time of turbulent cell sizes experienced during the ocean water experiments. Transition times are calculated for cells ranging in sizes comparable to, and larger than, the beam diameter passing, with a drift velocity of the turbulent structure encountered during BOTEX ( $\approx 0.5$  m/s). Furthermore, in order to account for cells with indices of refraction larger and smaller than the mean, the amplitudes of individual pulses were randomly varied between values of  $+1$  and  $-1$ . The series length and sampling frequency of the simulated pulse trains were chosen to be consistent with the frame rate (300 fps), and the number of images (2179 frames) recorded by the camera. Sections of the simulated pulse series are shown in the top left panel of Fig. 3. The two series of simulated deflections, longitudinal and transverse to the flow direction, were used as orthogonal coordinates to calculate the deflection along angles from  $0^\circ$  to  $360^\circ$ . The Fourier transform magnitudes of 13 such simulations are averaged to produce the lower two graphs on the left side of Fig. 3. The simulation is in good qualitative agreement with the measurement (right side of Fig. 3), a result justifying the assumption that index variations are reasonably well modeled by spherical cells. We would like to point out that the noise-like appearance of the Fourier transformed simulated beam wander signal stems from the previously mentioned phase interaction in the frequency domain and is very similar to the noisy appearance of the experimental dataset. It is therefore

reasonable to conclude that the noisy appearance of the measurement is due to the principle of the method and not due to actual measurement noise. As of now, no attempt was taken to scale the deflection magnitude and frequency due to cells of different sizes. This will be examined in future studies using known turbulent spectra such as the Kolmogorov spectra or more sophisticated power spectra recently suggested for the ocean [10]. Since the transition time of turbulent cells is determined by their size and the speed of the flow, it is conceivable that by using a more realistic power spectrum in the model, the velocity of the turbulent flow can be extracted from the shape and frequency content of the Fourier transformed deflection signals. Also, in the discussion above, the assumption was made that the flow is unidirectional throughout the beam path. A multidirectional flow would likely be indicated by the loss of the Fourier transform's anisotropy.

Commonly, cross correlation of the scintillation pattern of spatially separated propagation paths is used to remotely determine the cross-wind direction, the method thus requiring two spatially separated detectors. The technique described in this Letter allows for the determination of flow direction and, potentially, flow velocity with a single position-sensitive detector monitoring a single beam. While in this work a sophisticated high-speed CCD camera was used to record the beam wander, in future applications a simple position-sensitive quadrant detector could suffice to monitor beam wander, and hence determine the flow direction of optically active turbulence.

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